TMO TECHNOLOGY DEVELOPMENT PLAN

In Situ Communications Work Area

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OBJECTIVE: Increase the performance while reducing acquisition cost of planetary relay communications systems.

GOALS and SIGNIFICANCE:
The goal of this work area is to identify and, where appropriate, develop technology that will enable in-situ vehicles such as Mars landers and rovers to communicate reliably with Earth using low orbiting relays and/or stationary satellites (e.g.MARSATs). MARSATs are be the key to continuous contact and multimegabit data rates essential for human exploration of Mars. Low relay cost systems are of significance to the Mars Exploration Program, missions to other planets and objects in the solar system, and to TMOD who must ultimately terminate the link.

PRODUCTS:
The products for FY 98 are: 1) A MARSAT study report. 2) Relay protocols for M'01 and future missions., 3) Integrated UHF antenna & solar array for rovers /landers. and 4) Analyses of onboard vs iterative decoding. Additionally, multi-mission UHF relay studies were completed by industry (Cincinnati electronics and Motorola) in late FY 97.

DESCRIPTION:
Missions to the surface of planets and other heavenly bodies rely on small remote vehicles. By their nature, such vehicles are incapable of a direct to earth link with the Deep Space Network (DSN). Direct to Earth radio links of the same capacity would require a several orders of magnitude larger and unaffordable DSN antennas. Instead we must depend on light weight, low energy, links over relatively short distances to an orbiting relay satellite, which in turn completes the astronomically long link to Earth. These small rovers and landers require simple and efficient radio relays using efficient antennas that don't shadow solar cell arrays , efficient modulation and coding schemes that minimize energy consumption and protocols that interoperate accross missions. Low orbiting relays offer approximately only two 6-minute contacts a day at mid latitudes on Mars. Future human exploration Mars, or scientificaslly more intensive robotic missions, will require MARSATs for continuous contact and multimegabit data rates. A key feature of this effort is to work with industry to proffit from their developments in the commercial and defense sectors. This minimizes development costs for both NASA and industry. The WORK UNITS describe this in detail in the following pages

DELIVERABLES:
UHF multi-mission relay system definition and design in time for M'01
MARSAT study final report
UHF relay protocols for M'01 and plan for future missions in time for M'01
UHF patch antenna design and breadboard in time for consideration on the M'01 Rover
Decoding trade studies

RESOURCE REQUIREMENTS BY WORK UNIT:

	JPL Account #	FY98	FY99	FY00	FY01	FY02	FY03
Mars Areostationary Relay Satellite (MARSAT)	462-42010-331	60	0	0	0	0	0
Mars Relay System Protocols	462-42011-331	65	0	0	0	0	0
UHF Telecom Antenna	462-42012-336	75	0	0	0	0	0
Probe-orbiter-Earth link optimization	462-42013-331	50	0	0	0	0	0
Total	*462-420*	250					
Total Workforce		1.5					

TMO TECHNOLOGY TASK DESCRIPTION

TITLE: Mars Areostationary Relay Satellite (MARSAT)

WORK UNIT IN WHICH FUNDED: Mars Areostationary Relay Satellite (462-42010-331)

WORK AREA: In Situ ComNav

BRIEF TECHNICAL SUMMARY:

This task will provide a strawman mission design, including characterization of telecommunications performance and lifecycle costs, for a Mars Areostationary Relay Satellite (MARSAT, Figure 1) capable of supporting near-continuous, High-Definition TV communications bandwidths from sophisticated Mars landers and rovers and, ultimately, piloted Mars missions. The study will show how the aggressive use of telecommunications and propulsion technologies can provide a capability for near-continuous, high-bandwidth trunk lines from Mars in the coming decade.

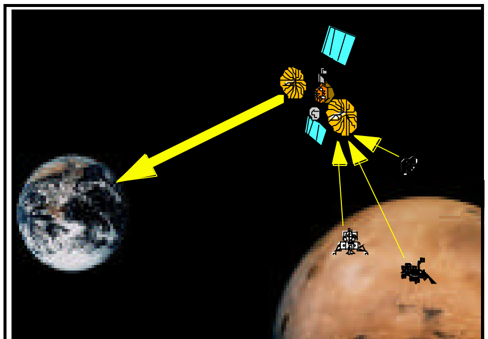

Figure 1: MARSAT "trunk line" providing continuous, high-bandwidth communications to Earth

JUSTIFICATION AND BENEFITS:

The spectacular success of the Mars Pathfinder mission has greatly increased the scientific and public interest in Mars. At the same time, Pathfinder provides a graphic illustration of the limitations of current Mars communications link capabilities. Scaled to maximum Earth-Mars distance, the Pathfinder telecom link only supports about a 1 kbps data rate into a DSN 70m antenna. For a public used to tens-of-kbps modems, and a science community used to 10-100 Mbps networking, such a link introduces an enormous bottleneck which affects our ability to do science and our ability to engage the public.

The recent Mission to the Solar System (MttSS) roadmap documented the benefits as well as the technological feasibility of high-bandwidth "trunk lines" from key solar system targets to support greatly increased communications bandwidths. With aggressive but realistic application of either RF or optical communications technologies, it should be possible to provide 10 Mbps data return from Mars to Earth, four orders of magnitude beyond Pathfinder, in a five-ten year time frame. 10 Mbps corresponds roughly to the communications bandwidth required to support High Definition TV, after application of state-of-the-art video data compression. Bandwidths of this magnitude will provide direct benefits for long-range rover operations, science analysis, and public outreach, and will be a necessity for piloted missions to Mars. In addition to the use for support of high-resolution video transmission, these high bandwidths will also support new classes of high-rate science instruments like imaging spectrometers.

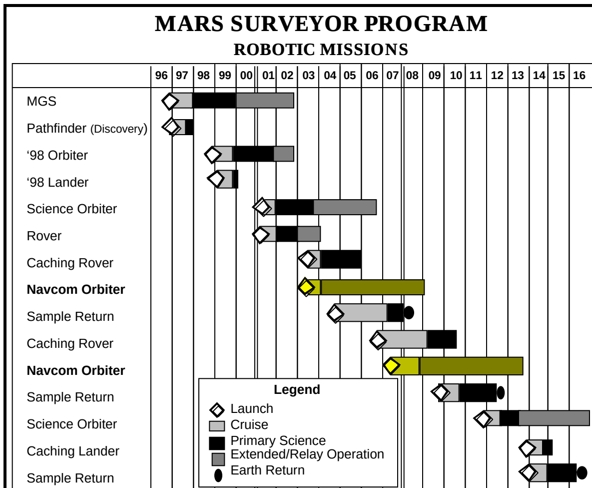

Figure 2: Mars Surveyor Program of robotic missions, including relay orbiters for navigation and communications.

Currently planned Mars communications orbiters are in low, polar orbits, which provide several very short (<10 minute) contact periods per day. An areostationary orbit would allow near-continuous relay capability between landers and Earth, again providing fundamental changes in the way we would use the link and the way we would operate Mars surface assets. Round trip light times will continue to drive the need for high levels of autonomy and embedded intelligence on Mars landers and rovers, but high-rate, near-continuous communications links will allow much higher levels of interaction between science investigators on Earth and their science instruments at Mars.

As shown in Figure 2, MARSAT would fit well into the Mars Exploration Program's mission set. The proposed MARSAT concept would be a candidate for a second generation Mars communications orbiter, in the 2007 time frame. If costs can be kept sufficiently low, it might even be a candidate for supporting long-range rovers in the 2003-2005 time frame.

APPROACH AND PLAN:

The MttSS roadmap effort included an assessment of projected communications capabilities for Mars-Earth trunk line communications, based on extrapolations of current technology trends. As shown in Figure 3, The envelope of capabilities reflects the range of performance possible assuming conservative or aggressive assumptions for both RF and optical communications options. Data rates of 10 Mbps can be achieved from Mars with large aperture, high-power RF systems; a 100W X-band transmitter and a 5m spacecraft antenna can deliver this data rate into a 70m DSN antenna. Recent RF technology advances in inflatable antennas and efficient, high-power transmitters, along with the high solar flux of 160 W/m^2 at Mars, will make RF systems like this feasible. Similarly, a 30 cm optical telescope at Mars can deliver 10 Mbps into a 10m optical photon bucket on Earth. The X2000 program will be developing a prototype optical communications package that approaches this capability, and TMOD is planning for implementation of 10m optical ground stations in the next decade.

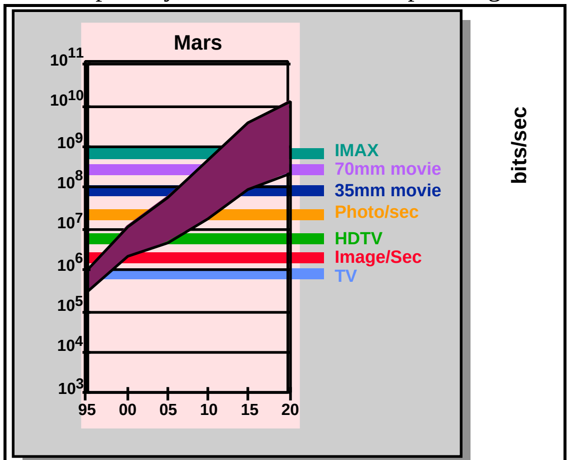

Figure 3: Projected Mars-Earth "trunk line" communications capability, from Mission to the Solar System Roadmap

Whereas the MttSS roadmap study addressed the feasibility of such systems, this study will take the critical next step of providing a strawman system design, identifying key technology development needs, and understanding the lifecycle mission costs for achieving these bandwidths in the next decade. The proposed approach would start by working with the Mars Exploration Program Directorate (for robotic missions) and JSC/HEDS representatives (for piloted missions to refine the desired MARSAT capabilities in terms of anticipated Mars communications requirements. Next, a rapid study would be performed with Team X to establish a baseline MARSAT design and cost estimate. The results of this study would be used as a starting point for targeted trade studies looking for opportunities to apply technology to improve performance and reduce cost, relative to the Team X baseline. The final study results would be documented in a TMOD white paper as well as a TDA Progress Report.

A number of key technology trades will be considered as part of this study. The performance, cost, and benefits of RF and optical trunk line communications systems will be examined. The characteristics of the in situ relay links will be explored, leveraging off of the studies being performed this year, in response to a TMOD RFP, by Cincinnati Electronics and Motorola. Various propulsion schemes will be explored, with the goal of reducing the cost of placing communications relay assets at Mars areostationary altitude: solar electric propulsion trajectories (spiraling out from low-Earth orbit and spiraling in to Mars areostationary orbit) will be analyzed as a low-cost alternative to a conventional aerobrake/chemically-propelled-periapse-raise approach to understand if the cost of the SEP system is more than offset by reduced launch vehicle costs. Throughout the study, interim status presentations will be made to a joint MEPD/TMOD steering committee, to provide programmatic guidance and technical feedback.

DELIVERABLES:

FY98 Q1:	IOM documenting high-level mission goals, to serve as input to Team X MARSAT study.
FY98 Q2:	Preliminary MARSAT study report by Team X.
FY98 Q3:	Follow-up investigations (documented in IOMs) on technology innovations that could reduce cost or increase performance relative to Team X study
FY98 Q4:	TMOD white paper, TDA Progress Report on MARSAT mission design, performance, and lifecycle cost estimate.

RESOURCE REQUIREMENTS:

	Prior Year(s)	FY98	FY99	FY00	Total at Completion
Funding ($K)		60			60
Workforce (WY)		0.4			0.4
Co-funding ($K)					
Projected Savings ($K)					

TMO TECHNOLOGY TASK DESCRIPTION

TITLE: Mars Relay System Protocols	
WORK UNIT IN WHICH FUNDED: Mars Relay System Protocols 462-42011-3310	
WORK AREA: In-Situ Communications	

BRIEF TECHNICAL SUMMARY:
We will develop medium access control (MAC) and automated repeat request (ARQ) protocols for Mars relay missions. The MAC protocol will allow relay elements to efficiently manage multiple landed elements within the relay elements' footprints on Mars. The ARQ protocol will ensure that only "good" telemetry is forwarded from the relay element to Earth, and that commands are quickly and correctly transmitted to the landed elements.

JUSTIFICATION AND BENEFITS:
JPL is planning at least one Mars launch during each opportunity through 2005, and possibly beyond. To increase the total bandwidth for communicating with Earth, many of the smaller elements destined for the Martian surface will relay information to Earth through orbiters or large landers.

The MAC and ARQ protocols we develop will provide flexibility, redundancy, and multi-mission compatibility for these relay missions. A flexible scheme will allow a given landed element to use any one of possibly several relay resources available to it. This increases the landed element's communication opportunities and enables redundant relay elements. Finally, a common set of protocols is necessary for the required forward and backward compatibility from mission to mission.

APPROACH AND PLAN:
We will begin by reviewing the requirements and operational scenarios of upcoming Mars missions. We will then design a MAC protocol layer capable of supporting the number of elements we expect to see in a typical relay element footprint on Mars. This may place constraints on the physical layer if, for example, we find that multiple simultaneous uplinks are required and are best supported by FDMA. We will then go on to design a simple ARQ scheme for the lander–relay link that will provide reliable data delivery.

DELIVERABLES:
At the conclusion of this project we will deliver protocol specifications for medium access and reliable data transmission through ARQ, along with performance analyses for the protocols' performance in sample Mars missions.

RESOURCE REQUIREMENTS:
This task will require one person nearly half time through all of FY98.

Savings will come from reduced development costs of future missions and through reduced mission operations costs, since fewer requests for retransmission of telemetry data will be needed from the DSN.

	Prior Year	FY98	FY99	FY00	FY01	Total at Completion
Funding ($K)		65				65
Workforce (WY)		0.4				0.4
Co-funding ($K)						0
Projected Savings ($K)			30	40	30	100

TMO TECHNOLOGY TASK DESCRIPTION

TITLE: Multi-Mission Low-Mass Compact Highly Efficient UHF Telecom Antenna

WORK UNIT IN WHICH FUNDED: Multi-Mission Low-Mass Compact Highly Efficient UHF Telecom Antenna; 462-42012-03360

WORK AREA: In Situ Communications

BRIEF TECHNICAL SUMMARY:

Our long-term objective is to develop low-mass and compact 400 MHz UHF telecommunication antennas that are highly efficient and can be used by many future missions with relay needs. The antennas will be used by remote elements such as rovers, landers, penetrators, balloons, and orbiting relay spacecraft.

The short term objective is to develop a UHF microstrip patch antenna that is capable of integrating with the solar array of the Mars rover. Since the microstrip patch antenna radiates only through its four edges and the patch is quite large ($\approx$ 30 cm) at the UHF frequency, the top of the patch can be attached with solar cells and not affecting the patch's radiation characteristics. Consequently, the UHF patch antenna can be placed beneath the solar panel with four slots opened in the solar panel for the patch's edges to radiate and, thus, forming an integrated antenna/solar panel structure.

JUSTIFICATION AND BENEFITS:

The 400 MHz UHF band is chosen because of the low propagation loss over the commercial 900 MHz and 2 GHz bands. However, the antenna's physical size, even for a low-gain radiator, is quite large at 400 MHz. By integrating the relatively large UHF antenna with the large solar panel, significant real estate and mass savings can be achieved for the rover. A rover with lower mass and smaller size translates into lower required power and, thus, cost saving to the program.

APPROACH AND PLAN:

Two types of microstrip patch antennas, for performance trade-off purpose, will be developed to be integrated with the solar panel. One is a square patch with relatively simpler design but narrower beamwidth, and the other is a crossed-slot patch with somewhat more complex design but more desirable wider beamwidth. These antennas will be designed (by already available computer software), fabricated and tested in-house. Among the two types, one will be chosen to be integrated with the solar array, and its RF and solar performances will be tested.

DELIVERABLES:

A circularly polarized UHF microstrip patch antenna integrated with the solar array will be delivered. The antenna shall meet the following two basic requirements: mass of 1 kg or less and minimum gain of –1 dB over an angular region of ±70°.

RESOURCE REQUIREMENTS:

	Prior Year	FY98	FY99	FY00	FY01	Completion
Funding ($K)	0	75	0	0	0	75
Workforce (WY)	0	0.36	0	0	0	0.36
Co-funding ($K)						0
Projected Savings ($K)						0

TMO TECHNOLOGY TASK DESCRIPTION

TITLE: Probe-orbiter-Earth link optimization	
WORK UNIT IN WHICH FUNDED: Probe-orbiter-Earth link optimization	462-42013
WORK AREA: In-Situ Communications	

BRIEF TECHNICAL SUMMARY:

Analyze performance of probe-orbiter-Earth links with on-board decoding or with iterative decoding of the overall code on the ground (without on-board decoding). Select algorithm and technology for realization of space qualified on board decoder and analyze performance.

JUSTIFICATION AND BENEFITS:

Current probe-orbiter-Earth links use separate channel codes for the probe-orbiter trunk and for the orbiter-Earth trunk. Probe encoded symbols are received on the orbiter and quantized to 1 or 3 bits per symbol. This data is re-encoded on-board the orbiter and sent to Earth, where two separate decodings are performed.

A first method for improvement is to perform soft decoding on-board the orbiter and the re-encode the decoded bits. This method improves performance in terms of reducing the required transmitted powers (at probe and orbiter) and reduces the amount of storage required on the orbiter.

A second method, which builds on our understanding of turbo codes, treats the two encoders plus an additional interleaver between them as a single serially concatenated turbo code which can be decoded on the ground by a modified iterative method similar to turbo decoding. This method avoids the need of processing on-board the orbiter and may achieve even better performance than the first method. It has the potential for improving performance at minimum complexity.

In general, it is desirable to shift complexity (processing power) from the spacecraft to the ground. We have preliminary results indicating that serially concatenated codes are very robust and can be efficiently decoded even in the presence of errors within the encoding process, i.e., errors that occur in the probe-orbiter portion of the link.

We will study flexible methods for improving the probe-orbiter link or the orbiter-Earth link, or both, depending on where the improvements are most cost effective. Projected gains are on the order of 1 dB for interleaving without on-board decoding, an additional 1 dB for on-board decoding, and another additional 1 dB or more for turbo coding/decoding (with no-onboard decoding).

APPROACH AND PLAN:

In this task we plan to explore how to meet link requirements subject to constraints on probe/orbiter link capability, orbiter/ground link capability, or processing capability on-board the orbiter.

We plan to analyze the performance/complexity of some of the following approaches.

Approach 0 --- In this method the orbiter simply quantizes symbol data from the probe, prior to re-encoding for transmission to Earth. There is no on-board decoding. This method has three variants:

- Approach 0a uses 1-bit quantization for symbols received at the orbiter.
- Approach 0b uses 3-bit quantization for symbols received at the orbiter.
- Approach 0c uses 1-bit quantization for symbols received at the orbiter, and interleaving on the orbiter.

For each variant we have made some very preliminary estimates of performance. These estimates are based on an oversimplified assumption of identical probe-orbiter and orbiter-Earth codes, i.e., the same “cost” for the two channels. This of course is not true in real situations, and a more realistic model will be used in this study. The characteristics of approach 0 is minimal on-board processing, but poorest overall performance. This method was used for the Galileo mission.

Approach 1 --- In this method the orbiter decodes the data received from the probe, prior to re-encoding for transmission to earth. In order to completely specify this method we need to select appropriate code(s) for the probe, and to design an appropriate space qualified decoder for the orbiter. This approach has a better performance that any of the variants of approach 0, but requires significant processing power on the orbiter.

Approach 2 --- In this method the orbiter re-encodes the noisy received probe data. The overall system is a concatenated coding system plus an extra noise component due to the probe-orbiter trunk. This method has two variants:

- Approach 2a uses 1-bit quantization for data received on the orbiter, and combined Viterbi decoding on the ground.
- Approach 2b uses 1-bit quantization, an interleaver prior to re-encoding (inner code) on the orbiter, and combined turbo decoding on the ground.

The challenge here is to develop suitable strategies for processing noisy symbols from the probe.

The advantages of the new approaches 1 or 2 are performance improvement s compared to approach 0, and adaptability to various SNRs on probe-orbiter and orbiter-Earth links. The choice between approach 1 and approach 2 offers flexibility to tradeoff higher processing requirements on orbiter (approach 1) for higher processing requirements on Earth (approach 2).

Approach 2b is essentially a serially concatenated code with interleaver. This code is composed of an outer code (the probe code in this case), an inner code (the orbiter code), and an interleaver between the two, which can be placed at the probe or at the orbiter. JPL is at the forefront in the development of serially concatenated codes (a NASA/Caltech patent application on this subject was filed in May 96), and performance results for this codes are very encouraging. In this task we are essentially suggesting to use the same concept of serial concatenated code, where the encoders are not co-located and errors due to the probe-orbiter link are to be accounted in the design of the overall turbo decoder. Our intuition, based on extensive experience with iterative decoding methods, suggests that the performance of approach 2b should be the best of all approaches.

DELIVERABLES:

- Characterize tradeoffs (performance/complexity) for some of the approaches described above
- Design or select codes for those approaches
- Select algorithm and technology for realization of space qualified on board decoder and analyze performance

RESOURCE REQUIREMENTS:

	Prior Year	FY98	FY99	FY00	FY01	Total at Completion
Funding ($K)	0	50				50
Workforce (WY)		0.3				0.3
Co-funding ($K)						0
Projected Savings ($K)						0